Flow Characteristics of Indian Blast Furnace Slag

Thesis submitted to
National Institute of Technology, Rourkela
For the award of the degree

of

Master of Technology
In
Metallurgical and Materials Engineering

by

Ankit Singhal

Roll No: 213MM1475

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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MAY, 2015

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING
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- 769008

CERTIFICATE

This is to certify that the thesis titled ***"Flow Characteristics of Indian Blast Furnace Slag"***, submitted to the National Institute of Technology, Rourkela by **Mr. Ankit Singhal**, Roll No. **213MM1475** for the award of Master of Technology in Metallurgical and Materials Engineering, is a bona fide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The Thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a Master of Technology degree in Metallurgical and Materials Engineering.

Prof. Smarajit Sarkar
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ABSTRACT

A study of the flow characteristics of Indian Blast furnace slag is necessary to study the softening and melting phenomenon in the blast furnace which highly affects the size and position of the cohesive zone. It also affects the operation in the blast furnace, hot metal quality and the consumption of the reductant. In the current work, the flow characteristics of high alumina synthetic slag (Al_2O_3 25%) are determined by Leitz-Wetzlar high temperature microscope resembling different Indian blast furnace slag. The C/S ratio was varied from 0.9-1.2 and MgO was varied from 4-10 %. It was observed that the softening, hemispherical and flow temperature increases with an increase in the C/S ratio. Increase in the MgO content increases both softening and flow temperature. In addition, an effective statistical model is developed through constructing empirical equations by regression analysis method to predict softening temperature (ST), hemispherical temperature (HT) and flow temperature (FT) based on CaO/SiO_2 ratio, MgO and Al_2O_3 content. Calculated values of ST, HT and FT using this empirical relation based model correspond well with results obtained experimentally from hot-stage microscope. This well validated statistical model based on empirical equations will be useful in predicting the flow characteristics temperature for blast furnace slag.

Keywords: Softening, C/S ratio, Flow Characteristics, Statistical model.

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CHAPTER - 1

INTRODUCTION

CHAPTER – 1 INTRODUCTION

1.1 . Introduction

Iron making through the blast furnace route will probably be the most important process for the production of hot metal which is finally converted into steel. India consumes huge amount of coking coal which is being utilized mainly by steel industries. It is therefore necessary to understand the factors responsible for affecting the smoothness of operation, consumption of the coke and hot metal quality which is produced and over all, the related green-house problem.[1]

The Blast furnace process works on the principle of counter current flow, where the solid charge coming downwards meets with the hot gasses moving upwards mostly consisting of reducing gases and nitrogen. Obviously the temperature, composition and gas-pressure of the burden greatly affect the process. While most of the charge material descending soften and melt at relatively higher up the furnace, the coke lumps stay solid and are responsible for keeping the bed open even at the tuyere zone. On the other hand the softened or melted solid affect the permeability of the bed and also restricts the gas flow which allows the movement of gas through the gaps of the slits of coke. Due to this the pressure is dropped and affects the gas-solid-liquid boundary which greatly affect the slag metal rate of reaction and finally the blast furnace process of iron making.[2]

Blast furnace is made up of number of zones. Some important zones are the cohesive zone, granular zone, the bosh and the hearth. Out of these the cohesive zone is the most important. It is on the basis of the gas flow and permeability of the bed. Cohesive zone is just under the granular zone where the up moving gases containing CO start the reduction of the iron oxide in the ore. This type of reduction is termed as indirect reduction because the reduction is carried out by "CO" which is a product of "C‟ and "O_2‟ but not by "C‟ directly. The indirect reduction is a exothermic reaction while direct reduction is a endothermic reaction. If we will make use of indirect reduction more in the blast furnace, then there will be reduction in consumption of coke which is responsible for heat generation.[2]

In the cohesive zone, the softening and melting of iron containing materials begins with the help of the fluxing agents. The granular zone is extended and also the indirect reduction is enhanced.

This will lead to forming of cohesive zone lower down the furnace. For forming the cohesive zone lower down the furnace the softening temperature should be higher. The permeability in the cohesive zone is also affected by softening and melting.

The thinning of the cohesive zone takes place by high softening temperature and subsequent low flow temperature. If the cohesive zone is narrow, then the distance travelled by the liquid is less and will result in low Si pickup. Low Si pickup in the hot metal will improve its quality. At lower down the Bosh the final slag is formed and it should flow as soon as it softens. It should trickle down to the hearth in the furnace.[3][4]

Indian Blast Furnace slag mainly consists of Al_2O_3, SiO_2, CaO, MgO etc. which plays an important role in controlling the flow characteristics of slag. Al_2O_3 is amphoteric in nature and is one of the important constituent for determining the characteristic properties. If we increases the content of Al_2O_3 and SiO_2 (if the slag is basic), then it increases the viscosity of the slag because they are network formers. Al and Si occupy the similar sites in the lattice. But if the slag is acidic in nature, then addition of Al_2O_3 decreases the viscosity of the slag because it acts as a network breaker. CaO and MgO releases Ca^{+2} and Mg^{+2} ions, which are basic in nature. These cations are dispersed at random in the silica network. They reduce the strength of the Si-O bond and decrease the overall viscosity of slag. As compared to MgO, CaO is a stronger base which makes the slag basic. But if we increase the strongly basic Cao beyond a certain limit, then the viscosity can increase. This occurs due to increase in the chemical potential of some primary solid phases. So in order to maintain optimum basicity the less basic oxides are added like MgO.

Considering all the above factors an attempt is made to find the flow characteristics of synthetic slag prepared in the laboratory of different compositions resembling the Indian blast furnace slag. It is also aimed to develop a statistical model through empirical equations by regression analysis to predict the S.T, H.T and F.T.

CHAPTER - 2

LITERATURE SURVEY

CHAPTER-2 LITERATURE SURVEY

2.1. Introduction to Blast Furnace Slag

Blast furnace has a very high rate of production and it has great heat utilization. Due to this the blast furnace iron making process is the mostly used as compared to other iron making processes. Blast furnace is highly efficient and works on heat exchange by counter current principle. Many recent high capability blast furnaces have produced a large amount of 12000 tones of hot metal every day. India produces around 67 million tons of crude steel per annum out of which 57% is from the pig iron produced through the blast furnace. The raw materials need 7 to 8 hours to come down to the base of furnace where they finally develop into liquid slag and iron. These products are taken out regularly after some time. The hot air is blow from tuyere at bottom of furnace. This hot air moves up and takes 7 to 8 seconds to get to the top after passing various reactions. Blast furnace runs for 4 to 10 years continuously and only stops for short time to perform the planned maintenance.[5]

Controlling the characteristics of slag is very important for producing good quality hot metal. They remove the unwanted nitrides, oxides, phosphides and sulphides. However close controlling of the slag compositions is must. If not they can produce various problems and can cause trouble. The improper composition of the slag can lead to risky deterioration of S, P, Si and also various inclusions of oxide.[5][6]

The completely homogeneous liquid must be taken at the operating temperature in order to make effective blast furnace slag and practically achievable. The fluidity of the slag should be sufficient so that it can easily flow out of the Hearth without losing time for production. For getting a good quality hot metal, slag must have the following properties:[6]

- Removal of the impurities
- Best possible slag-metal reaction
- Entrapping of less metal through better slag-metal separation.

And for smooth operation of any blast furnace, the slag must satisfy the following requirements:[7]

- The volume of the slag should be kept as low as possible.
- It should have the characteristics of removal of alkali and fulfill the desulphurization requirements.
- Primary slag composition must be uniform.
- Slag should be formed up to a certain limited height and must be stable.
- Good permeability of the slag should be there in slag formation zone. The melting point of the slag should be neither too high nor too low.

If the cohesive zone is formed lower down the blast furnace, then it improves the productivity and coke rate reduces and in most of the cases the iron bearing material in the blast furnace gets the softening temperature (top end of cohesive zone) with a higher degree reduction more than 50 percent. The lowering and narrowing of the cohesive zone has three advantages:

1.) Enhancement of the indirect reduction as a result of extension of granular zone.

2.) The distance travelled by the hot dripping metal is decreased due to which less silicon is picked up hence improving the quality of hot metal.

3.) It reduces the extent of the impermeable zone in furnace that regulates the movement of gas/solid in furnace.

In blast furnace, as the burden comes down inside the furnace, the hot metal quality obtained is dependent on slag formation and its transformations. It is well-known that components of slag i.e. silica and alumina increases viscosity. Increase in CaO decreases the viscosity. Slag's melting zone determine cohesive zone of furnace. Hence for finding blast furnace productivity, main role is played by fluidity and melting characteristics. Initially slag which is rich in iron is created and after that the slag's composition varies because of intake of CaO and MgO from flux. As the slag comes down, it absorbs alumina and silica, created from coke's combustion. Trickling down process depends on the viscosity of slag. This is further regulated by the temperature and composition of melt.

2.2. Blast furnace operations

The main sources of iron are contained as ores which are oxides of iron. Main oxides are Fe_2O_3 (Hematite) and Fe_3O_4 (Magnetite). It also contains some small % of carbonates and hydroxides. Hematite is used mostly used of all ores for making iron. Hematite has about 71% of iron and magnetite contains nearly 72.5% of iron, when pure. But actually, there is 50-65% of iron content for ores which are rich. They have 35-50% for ores which are lean. Remaining are gangue consisting of alumina, silica, moisture and some water. The ores are generally charged as sinters or pellets. It is good and efficient to increase the iron content by purification process of ore containing low iron. By the help of crushing and grinding waste material can be removed from the ore and formed it into a powder called gangue. The gangue material is not soluble in melted iron. It has very high melting point. Although they fuse at lower temperature and forms a slag in the presence of fluxes. Magnesia helps in increasing slag's fluidity. Basicity is defined as ratio of lime (basic) to silica (acidic).

Coke is produced from mixture of coals. Firstly coal is trampled and made into powder form. It is then charged to an oven. Oil and tar is removed from the coal by heating in oven. It is taken out of the oven after completing 19 to 24 hours. Now coke is cooled down and made into pieces of 1 to 3 inches. The coke contains nearly 91 to 92 % carbon, sulphur and some ash. High permeability is provided by strong pieces of coke.

Fine raw ore, limestone, small coke and different iron containing waste (steel waste) are fed into the blast furnace by mixing properly in appropriate proportion and putting in the sintering strand which is bit a like conveyer belt. This mixture is being heated by the gas fired furnace fused by heating of fine coke. Liquid metal is formed from these fine ore, sinter and pellets.

Limestone is used as a raw material in a blast furnace and is extracted with explosives from earth's surface. It is final raw material in iron making process. By crushing it, it is made to a size ranging from 0.6 to 1.5 inch so as to form flux for the blast furnace operation.

All the raw materials are kept in a field of ore. Before charging, it is transported to stock house. After putting them on top of furnace, they move down and passes through various physical and chemical reactions.[5][6][7]

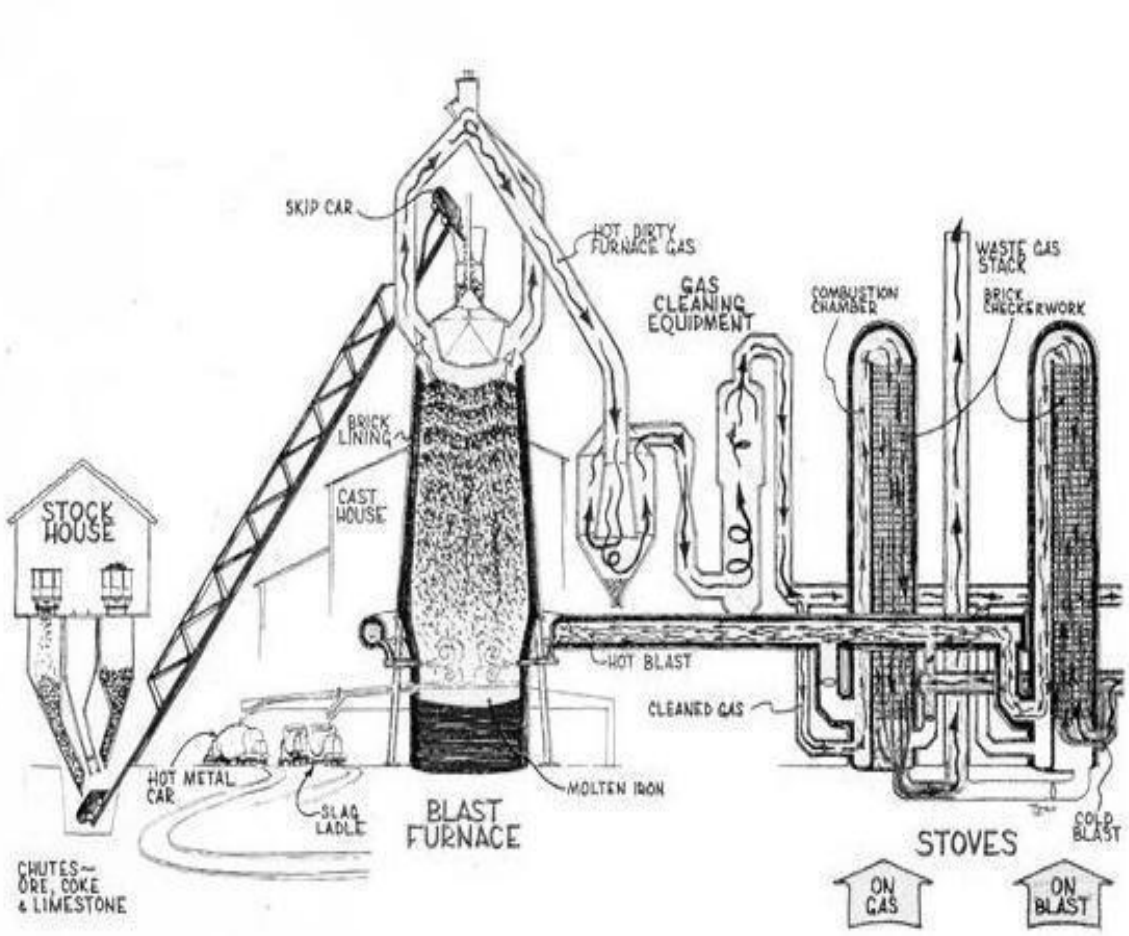


Fig. 1-A schematic diagram of Blast Furnace Process

The iron ore is reduced by help of various chemical reactions and oxygen is removed from the iron oxides. Reactions involved are:

- Starts at 850˚C

$$3Fe_2O_3 + CO = CO_2 + 2Fe_3O_4$$

- Starts at 1100°C

$$Fe_3O_4 + CO = CO_2 + 3FeO$$

- Starts at 1300°C

$$FeO + CO = Fe + CO_2$$

Or

$$FeO + C = Fe + CO$$

When it is passing through this reactions, then at the same time softening begins and finally melt. It comes down to bottom of furnace passing through coke after melting.

Coke moves down to furnace where preheated air enters the blast furnace. Ignition of coke occurs due to hot blast. It reacts to the air immediately and releases heat shown by the reaction:

$$C + O = CO_2 + Heat$$

Carbon monoxide is formed due to reduction of carbon dioxide at a high temperature due to the presence of extra carbon. There reaction as follows:

$$CO_2 + C = 2CO$$

Carbon monoxide, product obtained from above reaction is required for indirect decrease of iron oxide in previous chemical reactions.

The limestone and dolomite descends to furnace and went through 1st reaction while remaining solid:

$$CaCO_3 = CaO + CO_2$$

$$MgCO_3 = MgO + CO_2$$

This reaction is necessary for energy and gets started at temperature of 800-1000*C. Slag is formed by combination of gangue and basic oxides. Removal of sulphur is important from iron by help of CaO. It is required before conversion of hot metal to steel. Removal of sulphur can be shown as:

$$FeS + CaO + C = CaS + FeO + CO$$

CaS becomes element of slag. Slag is also formed from any remaining Alumina (Al_2O_3), magnesia (MgO), Silica (SiO_2) or Calcia (CaO), earth oxides, etc. with some minor other oxides and also sulphides that entered with the iron ore, pellets, sinter or coke. The liquid slag trickles down to the bottom of the furnace through the coke bed due to its low density and floats there over the molten iron.

Hot dirty gases products are also formed in iron making process. These gases go out from peak of furnace. It pass through gas cleaning equipment. There dirt is taken out from gas and gas is cooled. Since this gas has a good energy value, so it can be used to preheat the air by gas like a fuel in furnace called "hot blast stoves". It enters blast furnace to become "hot blast". Any of the gas which is not burned in the stoves is sent to face the boiler house and generates steam which rotates a turbo blower that produce the compressed air called "cold blast" that comes to the stoves.

Large number of physical and chemical reactions takes place throughout the furnace. Desired final product “hot metal” is formed. Composition of Hot metal follows:[8]

Iron (Fe)	= 93.5 - 95.0 %
Silicon (Si)	= 0.30% - 0.90 %
Sulphur (S)	= 0.025 - 0.050 %
Manganese (Mn)	= 0.55 – 0.75 %
Phosphorous (P)	= 0.03 – 0.09 %
Titanium (Ti)	= 0.02 – 0.06 %
Carbon (C)	= 4.1 – 4.4 %

2.3. Blast furnace internal zones

Composition and temperature fluctuates in blast furnace with height. It is taken constant along horizontal. But still some changes occur in horizontal directions also. It is shown by 2 reasons:

1) Localized combustion is carried out when hot air is moved through tuyeres. These gases moves upward and has no tendency to penetrate uniformly at centre.

2) Burden charged from top is not homogeneous. Unevenness occurs from centre to periphery due to varying density and size.

These zones influence the performance of the furnace and play a very important role. Construction of every zone depends on chemical, physiochemical and physical characteristics of burden.

Blast furnace has 6 zones. These are:

1) Granular Zone

2) Cohesive Zone

3) Active coke Zone

4) Stagnant coke Zone

5) Tuyere Zone

6) Hearth Zone

Granular zone is at top part of furnace. This zone contains coke and also irons containing material having small quantity of lime and fluxes. Lower down this zone, iron containing oxides reduces to iron and wustite. In this zone, indirect reduction by carbon monoxide plays an important role.

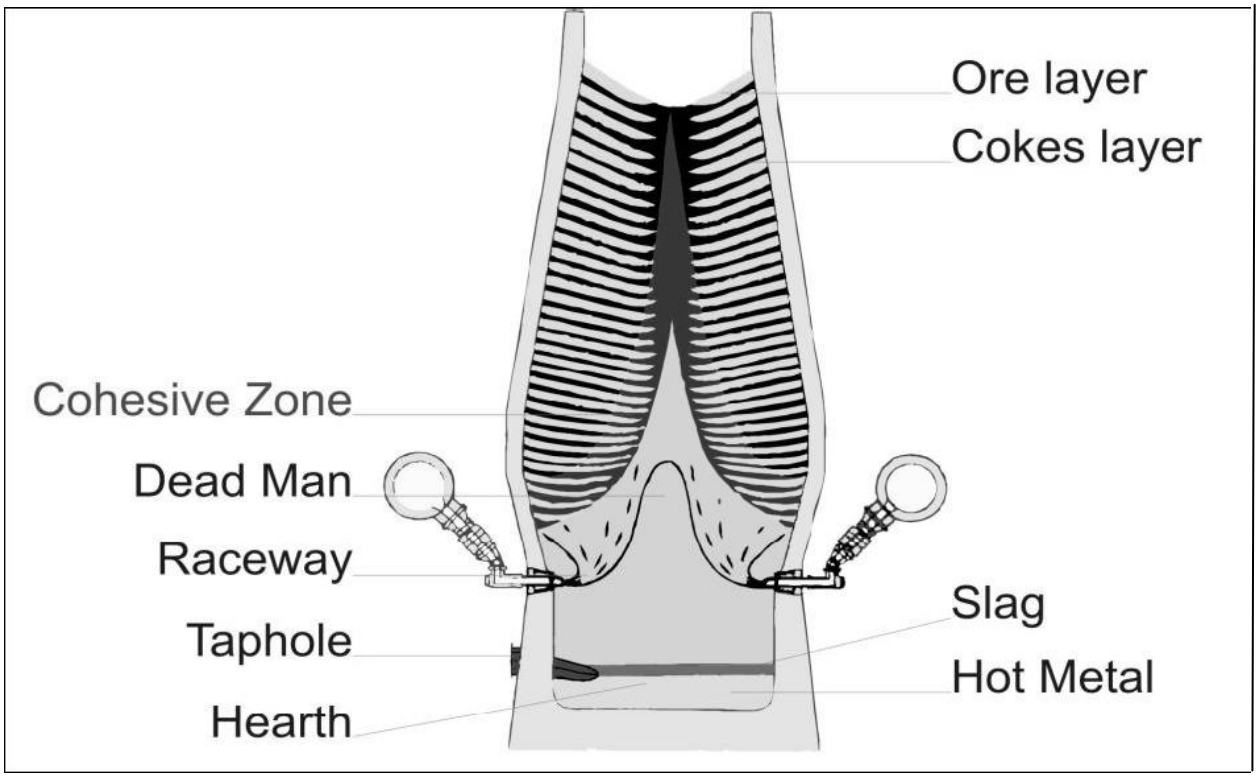


Fig. 2- Cohesive Zone

Cohesive zone is below the granular zone. When burden comes down more, temperature rises when comes in contact with more hot gases. Due to this, iron solids starts softens and finally melting.

Active coke zone is below the cohesive zone. In this coke participate in reaction involving iron oxide direct reduction by slag which comes down and CO_2.

Stagnant coke zone is below the active zone. In this zone, hot air has no tendency to go through furnace centre. Coke remains solid here. It supports all loads through which metal and slag comes down and saturation of metal occurs with carbon.

Tuyere zone is below the stagnant zone. Here coke is burned and combustion of carbon occurs when it reacts with hot air coming from tuyere holes. Coke gets in motion during motion and their place is taken by the fresh pieces.

Hearth is lowest region in Blast furnace. In this, slag and hot metal appears in 2 layers and taken out once in a while.[9][10]

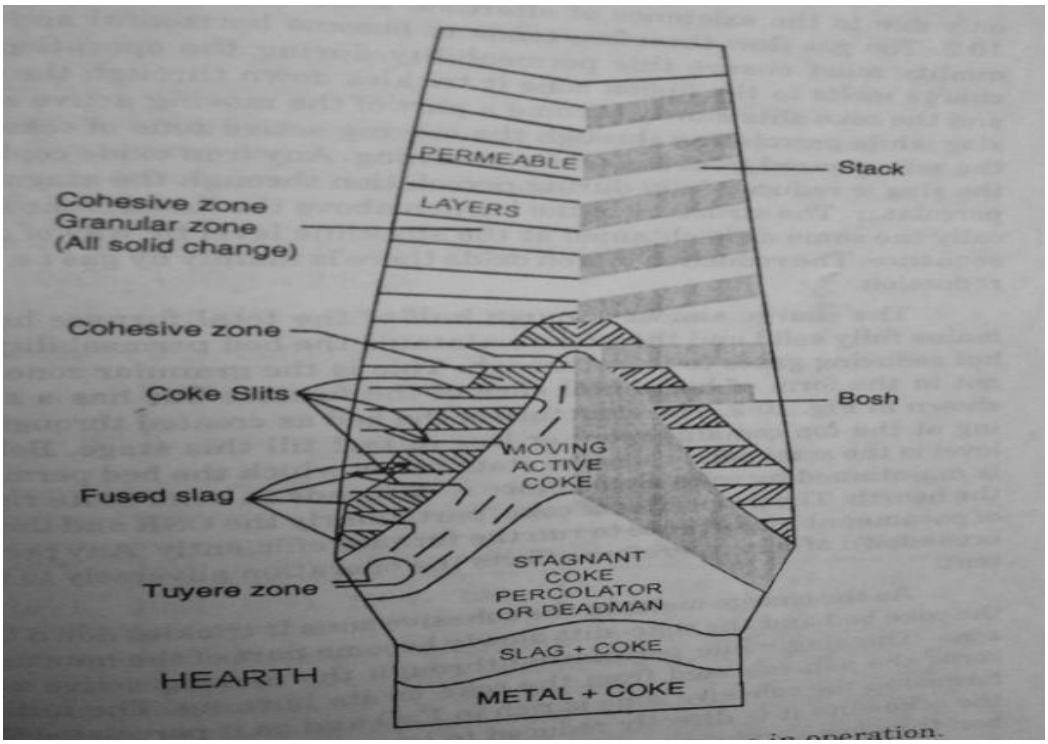


Fig. 2- General schematic of blast furnace internal zones

2.4. Reactions in the upper zone

A main reaction in blast furnace is reduction reaction of iron oxides. Product layers are formed during iron ore reduction. When reduction and chemical reaction rate is faster, then product layer formation is more.

$3\ Fe_2O_3 + CO = CO_2 + 2\ Fe3O4 + 10.34$ kcal (1)

$Fe3O_4 + CO = CO_2 + 3\ FeO - 8.76$ kcal (2)

$FeO + CO = CO_2 + Fe + 3.98$ kcal (3)

Iron oxides are passing through these purifying reactions at the same time. It begins to soften, melted and lastly comes down as iron (liquid) to bottom of furnace getting through coke. Reduction of Magnetite takes place to form wustite mainly at 700-900°C; thermodynamically deposition of carbon occurs from CO by reaction:

$$2\ CO = CO_2 + C + 41.22\ kcal \quad (4)$$

Deposition mainly occurs in a thin temperature range of 400-600°C, where catalysis of reaction takes place by iron and its oxides. H_2O is also reduced in the upper furnace by the CO to certain extent.

$$CO + H_2O = CO_2 + H_2 + 9.67\ Kcal \quad (5)$$

Decomposition of carbonates occurs at relatively low temperature other than those of calcium around 400° C. As modern furnaces are using pellets or sinter and these carbonates are calcined outside, so they are of very little importance.[5]

2.5. Reactions in the Middle Zone

This zone is about 4-6 m below the stock level and 3-5 m above the tuyere level. The temperature ranges between 800-1000°C and is a moderate temperature zone. It can take up to 55-60 % of shaft height and this height is considerable (nearly 70 % of volume of shaft) in recent furnaces. It takes around 2.5-3 hours to pass this zone.

For indirect reduction this temperature range (800-1000°C) is very important from the kinetic point of view. This is very good of wustite, which we get after reduction of magnetite and hematite in this part of furnace. Here lies a chemically inactive zone where gas composition doesn't change. Equilibrium is approached with wustite by CO and CO_2. Below 1000°C, indirect reduction of all iron oxides occurs and that of wustite at 800-1000°C.

Middle zone or indirect reduction zone in the blast furnace has a great importance and fuel economy is directly varied and depends on direct/indirect reduction.

So realization of their role is important. Direct reduction results in a thermal deficit but is economical for coke. Balance has to be maintained between reduction and thermal requirements. If the height of the 800-1000°C temperature range is large, the gas-solid contact time will be longer at these temperatures and the indirect reduction degree will be greater. Similarly the reduction will be more rapid if the reducibility of the ore is higher. In this region another important reaction occurs called as water-gas shift reaction:[5]

$$CO + H_2O = CO_2 + H_2$$

Hydrogen is generated by this reaction which is more active reducing agent as compared to CO.

2.6. Reactions in the lower zone

Lower zone is about 3.5-5 m on top of tuyere level to bottom of hearth. This zone has a temperature around 900-1000°C. It took around one to three hours for burden to come down to tuyere from the belly. In this zone molten materials temperature reaches 1400-1450°C and the up going gases cools down to a temperature of 800-1000°C. Continuous creation of voids is there due to the coke's combustion at face of tuyeres. This is reason for flow of charge materials down. An active area called raceway is resulted due to this combustion which is a ring of 1-2 m depth. Beyond the raceway, there is a dead man's zone which is closely-packed column of coke. The coke column in the hearth can be suspended on the molten iron or can reach the hearth floor. Some of the slag and iron particles are trapped in the coke voids which can be take out by tapping.

The gangue materials with addition of flux like dolomite or limestone begins to soften or fuse in this belly region. Here 2 different phases (FeO-SiO_2-Al_2O_3-MnO) primary slag having small quantity of CaO and partly carburized primary iron) begins to form at temperature above 1200°C. Mixture of this phase is estranged from one another. These liquid phases are separated from each other further down the furnace, which overtake on coke slits above raceway and is stored in hearth and taken out once in a while. Here the raceway works like a counter-current liquid-gas exchanger, as the tuyere gas moves up through voids or spaces present in coke bed. Mechanical support is also provided by coke.

For free running of the slag the temperature of the hearth which is about 1500-1550°C is necessary to make sure superheat in hearth. It is looked whether both of them are in liquid form in blast furnace operating circumstances. Important chemical and physical reactions happening in this zone:[5]

1.) Endothermic calcinations of limestone

$$CaCO_3 = CaO + Coke$$

2.) Direct endothermic reduction of FeO

$FeO + C = CO + Fe$

3.) Direct endothermic reduction of SiO_2

$SiO_2 + 2C = 2CO + Si$

4.) Direct endothermic reduction of MnO

$MnO + C = CO + Mn$

5.) Direct endothermic reduction of P_2O_5

$P_2O_5 + 5C = 5CO + 2P$

6.) Sulphur removal

$FeS + CaO + C = Fe + CaS + CO$

7.) Combustion of carbon (exothermic)

$C + O_2$ (air) $= N_2 + CO_2$

8.) Reduction of CO_2 (endothermic)

$CO_2 + C = 2CO$ (>1000°C)

9.) Reduction of moisture in blast (endothermic)

$H_2O + C = CO + H_2$ (>1000°C)

2.7. Blast Furnace Slag

2.7.1. Origin

For the iron's production, the iron ore, iron crumb, and fluxes are fed into the furnace along with the coke used as fuel. From combustion of coke the carbon monoxide produced, by which the iron ore is reduced to product of melted iron. It can be made into products and iron. It is mostly used for steel production.

A non metallic co-product is also produced called Slag in process. It consists primarily of alumina-silicates, silicates and calcium-alumina-silicates. Molten slag consists of nearly 20 % of production of iron, in which much of the sulphur is absorbed from the charge.[11]

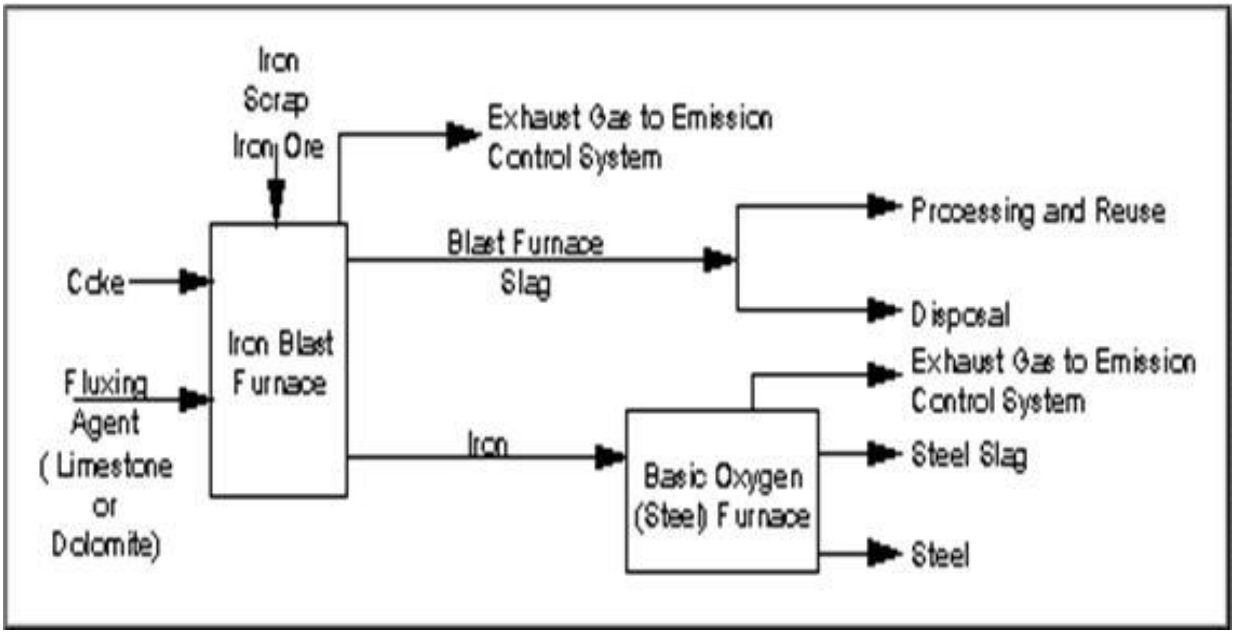


Fig. 3- Schematic diagram of blast furnace slag production and blast furnace operation

2.7.2. Forms of Slag

1.) Air-Cooled Blast Furnace Slag (Atmospheric Cooling)

When the liquid slag is poured into the beds and is cooled under the atmospheric condition, then one of the various slag products is formed. A slag produced is lump, hard and crystalline in structure, which is finally be crushed and screened.

2.) Pelletized Blast Furnace Slag (Accelerated Cooling)

It has been used to granulate blast furnace slag in which there is less use of water and slag is cooled rapidly through the air with high impelling of the viscous air. By calculating process, pellets are created crystalline and can be helpful for collective use. This pelletized blast furnace slag is used for the production of cement.

3.) Foamed or Expanded Blast Furnace Slag (Controlled Water Cooling)

If the molten slag is solidified and cooled by adding controlled quantities of air, water or steam, then the process of cooling and solidification can be accelerated. It increases the quality of cellular nature of the slag and produces a foamed product or lightweight expanded. Its low bulk density and relatively high porosity and helps us to differentiate between foamed slag and the air cooled blast furnace.

4.) Granulated Blast Furnace Slag (Water Quenching)

By rapid water quenching the molten slag gets cooled and solidified to a glassy state, crystallization can be neglected resulting in the formation of fragments of sand size, generally with some clinker-like material. According to slag's chemical composition, its temperature during water quenching, and the production method are the 3 factors responsible for the gradation of granulated slag and physical structure.

2.7.3. Slag Composition

The major constituents of blast furnace slag are alumina, calcia, silica and magnesia which comprise 95% of slag's total volume. Minor elements consist of sulphur, manganese and iron and compounds and some traces of several others. The major oxides are not in the free form in slag. In air-cooled BF slag, they are joined to form various alumina silicate and silicate minerals as founded in natural geological forms. In case of pelletized and granulated slag, these elements exist as primarily as glass. There are different types of slag depends on cooling method applied.

In the iron production, the blast furnace is charged with the iron ore, flux stone (limestone/dolomite) and coke as fuel. Two products are obtained from furnace:
Molten iron and slag. The slag primarily consists of the silica and alumina from the original one iron ore, combined with magnesium and calcium oxides from the flux stone. It comes out from the furnace in the molten state with temperature exceeding 1480°C.

It plays a important role as they protects the metal and removes the undesirable impurities. Generally a liquid slag layer covers the molten metal and carries out following functions:
(i) It seals off metal from the oxygen and prevents oxidation.
(ii) It removes undesirable elements (e.g. P, S) from the metal.
(iii) It helps to remove the non-metallic inclusions (e.g. by flotation etc.).
(iv) It reduces the heat loss from the metal surface and prevents "*skull formation*".
(v) In continuous casting of steel, liquid slag infiltrates regularly between metal and mould and it provides both control of the heat extraction and lubrication.

Major elements are:

- SiO_2 – 32-42%
- Al_2O_3 – 25-30%
- CaO – 32-45%
- MgO – 4-12%

Minor elements are:

- S – 1-2%
- FeO – 1-1.5%
- MnO – 0.2-1.0%
- TiO_2 – 1.01%
- K_2O+Na_2O – 1%

2.7.4. Blast Furnace Slag Structure

Liquid slags are homogenous melts which consists of oxides of silicon and also other elements. They are known to have electrical properties and consist of simple and also complex ions. Crystal study of the solid silica proves that 4 oxygen atoms are present at the corner and silicon at the centre forming a tetrahedron. Continuous network of this has 2 atoms of silicon bounded to atoms of oxygen. These tetrahedral can share only the corners so that when every oxygen atom at corner is shared, the substance that is formed will have an overall stoichiometric formula of "SiO_2". Si atom has 4 charges. As each oxygen atom of tetrahedron has the residual valence, therefore the SiO_4 group carries a 4 negative charges, i.e. $(SiO_4)^{4-}$.

In crystalline state, the tetrahedral arrangement of silicon and oxygen atoms is symmetrical. Solid structure doesn't undergo any sudden change on the fusion, as expected. In the molten or vitreous silica, structure becomes very distorted but most of the corner remains shared. The viscosity of the molten silica is very high (≈ 104 P) and the corners being linked very tightly in all directions in the vast network.

The group, $(SiO_4)^{4-}$ which is also regarded as a individual tetrahedron with the silicon at the centre and oxygen at four corners, which can be assumed to exist as the ion in complex silicates. Measurement of energy of activation for the electrical conductance and the other results designate that adding up of MgO, CaO to the molten silica outcome in collapse of 3-D silicon-oxygen networks into the ions of silicate. Breaking of bonds occurs by attraction between oxygen and silicon. This is dependent on their relative valances and the ionic radii.

When Magnesia or lime is added to the molten Silica, 2 silicon-oxygen bonds are opened up which gives rises to an open shared corner where oxygen is getting added, each oxygen carrying negative charge. The cations are distributed in the interstices of network, being localized near that of the charged oxygen. As metallic oxides are added in the increasing amount, the Si-O bonds gets break correspondingly, and the large ring type or globular silicate ions are formed. These become progressively smaller as metal oxide content increases. When strong silicate network breaks, viscosity of melted part decreases severely. Viscosity has influence on structure and also on composition. Viscosity will be less if the structure is more relaxed.[5]

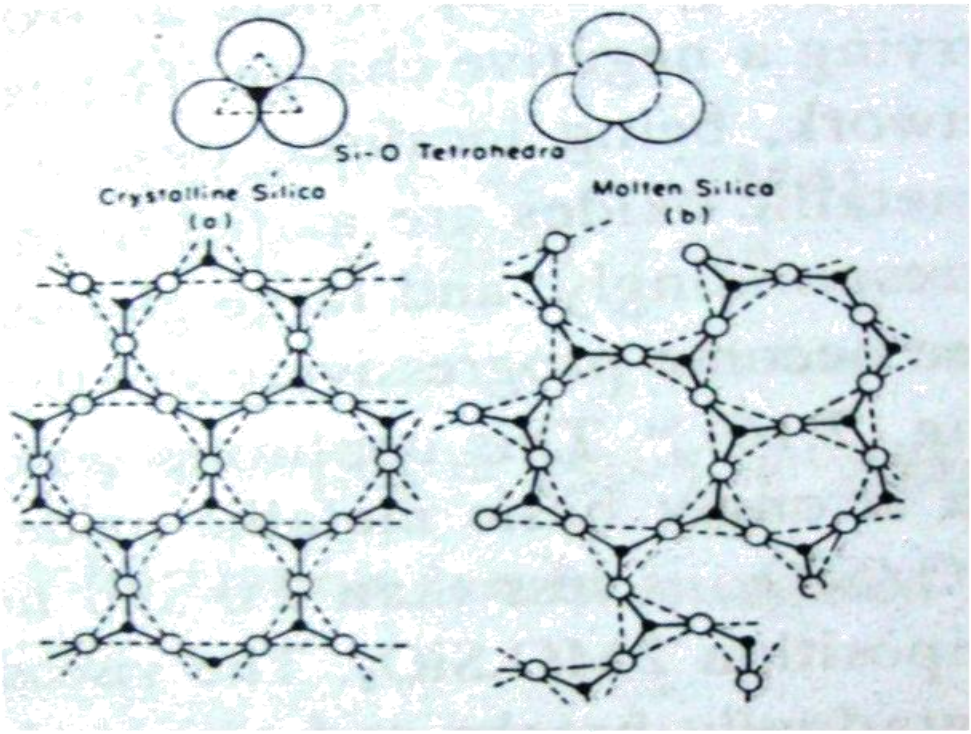


Fig.4*- Schematic diagram of silicate tetrahedron in the crystalline and the molten silica.Oxygen and silicon atoms are presented by the white and black respectively.*

2.7.5. Slag Viscosity

It is the transfer characteristic which compares kinetics of reaction and rate of reduction of end slag. Viscosity of slag steer movement of solid bodies through air and energy of furnace.

Slag shows as a Newtonian fluid under many applied shear stresses. Generally viscosity of Newtonian fluid doesn't depend on the presence of the shear stress. Viscosity is controlled by atomic structure and bond.

Viscosity depends on various factors. It has influence on transfer of heat and also chemical reactions occurring. Slag must have average viscosity i.e. not too low and not too high. Dispersion of ions in metal and slag have dependency on viscosity. De-polymerisation process decreases viscosity. 3-D network are broken into discrete groups when increasing basisity hence

decreasing viscosity. If basisity is further increased, then viscosity can increase due to rise of potential of chemical of solid. Easiness of slag removal depend on its viscosity.

Viscous behavior of the blast furnace slag plays an important role which affects the operation efficiency since flow pattern of the molten slag have a significant influence on the gas permeability, heat transfer and the reduction of the SiO_2 and FeO. Since reduction of iron ores and the formation of slag with the coke/coal ash gets precede in the blast furnace, basicity (CaO/SiO2) and the FeO content in slag continuously change from composition of the initial sintered ore. Because the slag do not get fully assimilate with the ash in bosh region of blast furnace, they exhibits relatively high (CaO/SiO2) ratios of about (1.4–1.6) and (5–20%) FeO, that is compared with the (C/S=1.2) and FeO $\leq$ 0.2 mass % in the tapped blast furnace slag. A relatively high basicity of the slag in bosh region is one of main causes of slag formation problems.[12]

2.7.6. Slag Liquidus Temperature

The liquidus temperature has a great influence on the effective positioning of the cohesive zone and width of cohesive zone that directly controls the productivity of blast furnace operation. The positioning and width of cohesive zone control the gas permeability, the Si content in the hot metal and extent of the indirect reduction occurring inside the furnace.

The various physicochemical properties of the slag play a vital role in the iron making since this influences the hot metal quality and also the process economy. All these properties not only affect blast furnace operations but can also increase the value of slag as a by-product. The impurities entering blast furnace in the form of various compounds are being removed in slag phase. The presence of these compounds as the impurity items influences the slag structure and also other properties. The slag must ensure the efficient removal of the impurities along with the smooth running of blast furnace processes. As from this point of view, slag characteristics are of the prime importance in the iron making operation.[13][14][15]

2.7.7. Softening and Melting phenomenon

When ferrous material changes its state, it is called softening of mass. Due to this permeability of bed is decreased and deformation rate is increased. Space is filled by small solid or liquid.

In the cohesive zone or mushy zone, at the same time different phenomenon occurs, softening and melting of oxide phases and softening and melting of metallic iron phases. Strength of metal phase will also depends on amount of the carbon present whereas strength of oxide phase depends on amount of the non-ferrous oxides or the slag formers present, also along with their distribution, the morphology and the chemistry. It will be also depend upon reduction degree as it affects availability of the iron oxide as the slag former.

Softening and melting phenomenon of ferrous burden is a very complex phenomenon and can be subdivided into the various steps. First oxide melt is getting formed at interface with the lowest melting point, usually between a iron oxide particle and the another oxide. So it is heavily dependent on phases present in and their distribution. First melt formed will wet the ore particles due to the reduction in the interfacial energy. This one liquid film will slow the reduction kinetics as it insert the another resistance to reaction i.e. an additional step of the transportation through liquid slag film. This is referred to as reduction retardation. It has been seen that in the majority of blast furnaces, metallic burden reaches the softening temperature with a very reduction degree more than 50 percent. Hence it can be assumed that the porous solid iron shell confining solid and the liquid oxides. When the liquid phase covers solid oxide particles, it becomes the semi-solid material, where liquid slag layer behaves as a lubricant for remaining particles. Due to result of wetting of ore particles by liquid slag, the core have much reduced mechanical strength and resistance to the deformation will be determined by the iron shell. Ability of the metallic shell to withhold the molten oxides together will also depend on their strength and also reduction degree. With the increase in the liquid volume fraction with the increase in temperature, a point will be reached when liquid will not be able to get hold by iron oxide. This will cause dripping of liquid slag from burden material. In meanwhile, reduced iron shell is being carburized, and temperature is being continuously rising. As liquid oxide fraction increases, it will also try to transfer from core to the metallic shell. This occurs due to reduction of the overall free energy as interfacial energy between the liquid and wustite which is larger than between the liquid and metallic iron. However it does not cause exudation of burden.[16]

Softening is defined as moment when metallic burden is not able to withstand the action of mechanical forces any longer. This generally coincides with dripping of material from the burden of component. The dripping is being a competition between increase in the liquid slag volume which increase pressure on the shell, and carbon content of iron shell, which also reduces its strength. Both of these parameters like to increase with the temperature. Reduction degree remains constant during this, because reduction kinetics is very slow after reduction retardation. Thus, dripping is being triggered by onset of the melting in oxide region, which is in equilibrium occurs at solidus temperature. Burden is then melted and moves down to hearth where hot metal layer and the slag layer is separated due to some difference in their density.[17]

2.7.8. Shortness of a Slag

Productivity and effectiveness is directly affected by softening and melting phenomenon. Flow temperatures noted are IDT, ST, HT and FT. ST shows plastic deformation. FT shows liquid flow of slag. "Short Slag" is defined as variation between FT and ST. It is desirable for fast coming down of slag after forming. It helps in exposing more sites of reaction for good metal slag reaction rate.

2.7.9. Flow Characteristics of Blast Furnace Slag

By using of a high temperature microscope, flow characteristics of the slag sample were determined. Under this four characteristics temperatures will be studied:[18]

1. Initial deformation temperature (IDT)
2. Softening temperature (ST)
3. Hemispherical temperature (HT)
4. Flow temperature (FT)

1.) Initial Deformation Temperature (IDT):-

At this temperature, ends of sample (cube shaped) are rounded up and change of shape is seen. Due to the stress concentration at the corners the shape of corners gets changed. Generally this temperature shows surface adhesiveness of slag.

2.) Softening Temperature (ST):-

It is the temperature at which shape of sample starts changing and at this temperature. Shrinkage of 1 division begins at this temperature. Generally softening temperature shows the beginning of the plastic deformation.

3.) Hemispherical Temperature (HT):-

At this temperature sample gets a shape like a hemisphere. At this temperature, altitude of sample is half of length of base. It is also called fusion or melting point. Generally this temperature shows slothful flow of slag.

4.) Flow Temperature (FT):-

At this temperature, the sample gets liquefied. It is taken when altitude of sample attains one-third of altitude at HT. Some papers also state that at this temperature, the height becomes one-third of original height. But 1^{st} one is more important and globally accepted. Generally it shows mobility of slag.

2.8. Effect of the slag basicity on viscosity of slag

Y.S. Lee et al [8] observed and studied viscous behaviour of the SiO_2-CaO-Al_2O_3-MgO-FeO slag. It was done under the conditions of 10 – 13 % Al_2O_3, 5 – 10 % MgO,0 – 20 % FeO and C/S = 1.16 - 1.6. Study of this type of slag by scientists lead them to conclude that there is de-polymerization of the silicate network above C/S = 1.3 to 1.5. This leads the viscosity of slag to increase. Slag viscosity goes up to ratio 1.3. This nice connection between viscosity and slag components was mostly due to thermodynamic approach in use up for activity of the primary solid workings. It was clear that high basic slag which has C/S > 1.3 is expected in chemical prospective in di-calcium silica.

Y.S.Lee, S.H.Yi, J.R.Kim and D.J.Min [19] proves transfer of mass, transfer of heat, FeO & SiO_2 lessening and permeability of gas depends on flow characteristic of slag. It shows affect on effectiveness and output by flow nature of slag. Behaviour of viscosity is studied of (SiO_2–CaO–MgO–Al_2O_3-FeO). C/S is 1.15-1.6, 10-13 % Al_2O_3, 5-20 % FeO, 5-20 % MgO. Viscosity of slag decreases up to C/S=1.3, with increasing basicity. Viscosity decreases by increasing FeO in slag.

Amitabh Shankar et al [20] for SiO_2-Al_2O_3-CaO-MgO & SiO_2-Al_2O_3-CaO-MgO-TiO_2 system by changing C/S ratio from 0.71 to 1.22. Temperature was from 1573 to 1873 K. Alumina content was wide-ranging between (21-28%). Magnesia was wide-ranging between (2-8%) and Titania was wide-ranging between 0-2 percent. It was proved that with increasing basicity, decrease in viscosity occurs. Viscosity vs. Temperature slope curve was coming very sharply of slag having low basicity.

J.-Y. Jia, G.-B. Qiu, C.-G. Bai, D.-F. Chen and Y. Xu [21] based on study of ternary slag (SiO_2-CaO-TiO_2), calculation model was formed. So a viscosity model was calculated at different compositions. Concentration of mass increases with rise in TiO_2. Decrease in viscosity is shown with rise in content of TiO_2. When temperature increases, viscosity is decreased and quality of running is good.

2.9. Effect of Al_2O_3 and MgO composition on the slag viscosity

Seong-Ho Seok et al [22] studied viscous behavior of SiO_2-FeO-CaO-MgO & SiO_2-Al_2O_3-CaO-MgO-FeO with addition of di calcium silicate and 8 % MgO. Basicity is high and temperature is around 1873 K. Viscosity was mainly dependent on content of alumina. Solid phase are extra in Al_2O_3 as compared to MgO.

Yasuji Kawai [23] studied viscosity of SiO_2-Al_2O_3-CaO-MgO and other molten slag. When MgO was added till 20 %, then viscosity decreases. It decreases when MgO was added furthermore. Section having less viscosity was large as compared to SiO_2-CaO-Al_2O_3.

Noritaka Saito et al [24] studied effect of CaO-SiO_2-Al_2O_3 slag by MgO on viscosity. They recommended through their experiment that the magnesia acts as a network changer and by adding MgO, decrement in activation energy occurs. They were able to illustrate through their experiments that viscosity of slag decreases with addition of MgO.

Masashi Nakamoto et al [25] used rotating cylinder technique to measure viscous behavior of the molten (CaO-SiO_2-MgO-Al_2O_3) and also compared result with the model that was created. They essentially wanted to study viscosity of slag that melts at the low temperature to improve blast furnace operations at the lower temperature i.e. about 1673K. They showed that the slag of following composition 35% Al_2O_3, 43.1% CaO, 7.5% MgO and 14.4% SiO_2 has a viscosity lower than 0.6 Pas below the 1673 K and it melts at about 1673K and below.

2.10. Effect of the slag basicity on liquidus temperature of slag

R.K. Verma et al [26] premeditated the effect of the basicity on softening and liquidus temperature of blast furnace type slag. They found that in general, liquidus and softening temperatures are somewhat high for basicity slags with high value. They studied liquidus and softening temperatures of slag in range of basicity (0.8-1.7). From results obtained, it was recommended that the basicity of around 1.05 is practicable in the Indian blast furnace.

CHAPTER-3

EXPERIMENTAL DETAILS

CHAPTER-3 EXPERIMENTAL DETAILS

3.1. Experimental apparatus

3.1.1. Abrasion Testing Mixer

The Abrasion Testing mixer is used to mix and grind the slag samples. The fixed 10 gm mixture of weighted percentage composition of all the major oxides (Al_2O_3-$CaCO_3$-SiO_2-MgO) is placed in the three plastic containers. The balls that are used to grind and mix are put in the plastic containers which are 6-7 in number. These plastic containers are then put in the 3 rotating chambers of the mixer. It takes around 6-7 hours to complete the one lakh revolutions which are appropriate for proper mixing. Mixing must be homogeneous and perfectly mixed.

Fig. 5- Abrasion Testing Mixture

3.1.2. High Temperature Microscope

This type of microscope is used for obtaining the characteristics temperature of the slag. The image of Leitz heating microscope is made known in Fig.6. The line diagram of the microscope is shown in Fig. 7. First of all, sample is made in shape of a 3 mm cube and the sample cube is put in electric furnace for heating in microscopic assembly. Camera is used for getting the photographs of the sample when its shape changes due to heating. Four characteristics temperature can be identified by the help of the grid division that was photographed at the same time with sample and also temperature where the sample was heated. According to German Industrial Standard 51730, four characteristics temperature can be shown as:

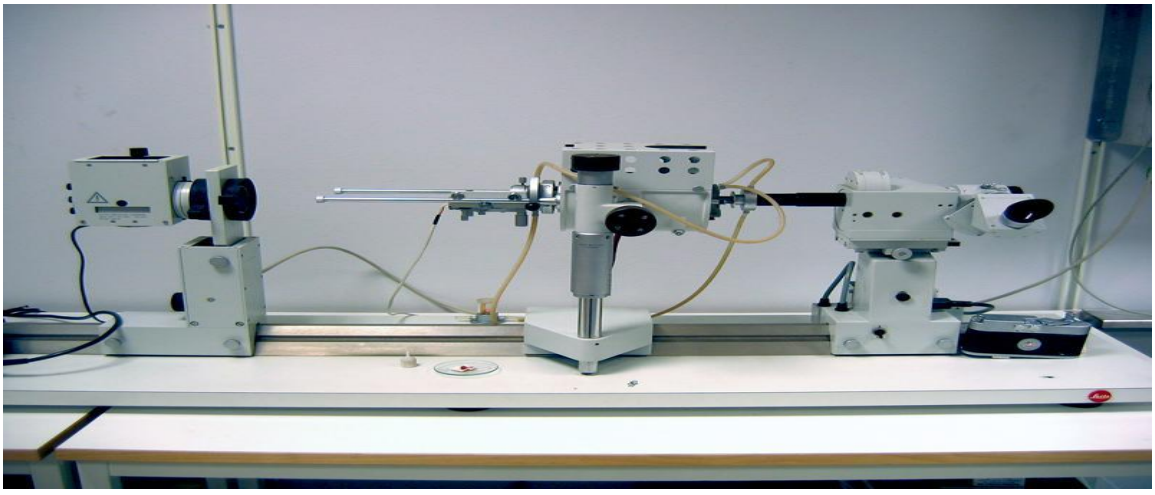


Fig. 6- Leitz high temperature microscope

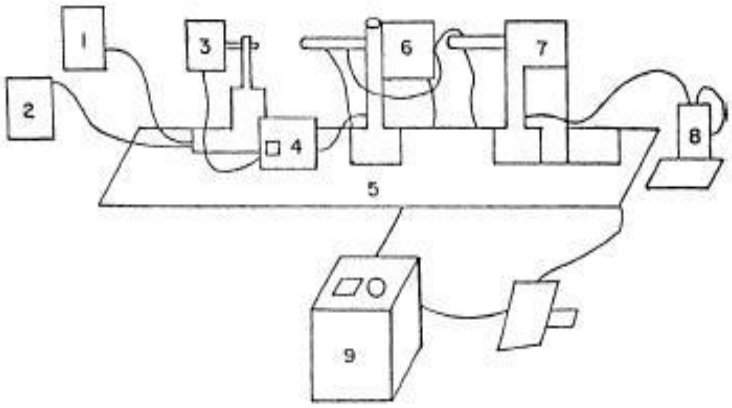


Fig. 7- Line diagram of the high temperature microscope

1- Cooling tank water
2- Cooling recirculating water tank
3- Light Source
4- Flexible transformer for light source
5- Optical bench
6- High temperature furnace(electrical) with specimen carriage
7- Photo and observation microscope
8- Digital thermometer
9- Regulating transformer

For finding the characteristics temperature, steps followed are:

- ✓ Sample is made into a 3mm cube and then heated inside the electric furnace in the assembly of microscope.
- ✓ When the shape of the sample is changed, then it is photographed by the help of the camera.
- ✓ Grid division is used to identify the four characteristics temperature of the slag.
- ✓ When the small deformation of the sample begins, it is taken as IDT.
- ✓ When the sample shrinks by 1 diivision or it gets soften, then it is taken as ST.
- ✓ When the sample acquires a shape of a hemisphere and its height to diameter ratio is 1:2, then it is taken as HT.
- ✓ When the sample's height is reduced to one third of the height of sample at HT, it is taken as FT.

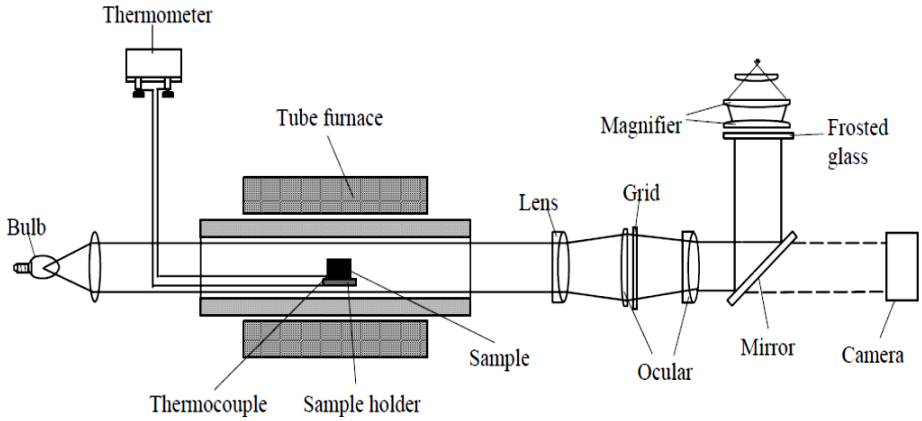


Fig. 8- Schematic diagram of the high temperature microscope

3.1.3. Sintering Furnace

The slag pellets made will be sintered at about 1600^0 C in the open hearth furnace to unite slag material with the help of diffusion. This temperature was taken as at this temperature only blast furnace slag comes out, so firing will be done at this temperature. If the mixing will be done homogenous, then firing will be proper. There is one crucible holder where platinum crucible is placed. After obtaining necessary temperature slowly but surely, the slag will be quenched in the water to the room temperature.

Fig. 9- Open Hearth Sintering Furnace

When the heating and and quenching is completed, the crucible used is cleaned by using diluted HCl (having 50% water + 50% Conc. HCl). The process of cleaning usually takes 2 days and after that the gel formed slag is washed out that was stucked in the crucible. Platinum crucible is used for firing in the furnace as elevated temperature is obtained for the duration of firing and platinum will be able to easily carry on at that temperature and is also non-reactive with slag and the outer atmosphere.

3.2. Experimental Procedure

Various types of slag were analyzed from different Indian blast furnaces of the various plants to get a basic idea of the composition of the synthetic slag and consequently a standard slag composition was determined. An Average Slag was taken and was arrived by taking mean of greatest and least composition that we received from different blast furnaces.

Slag compositions that were obtained will now be prepared from major oxides such as Al_2O_3, CaO, SiO_2 and MgO. These major oxides had been obtained separately from saleable market which is around 99% pure. We have not considered about the minor slag in our experiment.

3.2.1. Different Processes involved

A) Weighing:

After being furnace, the major oxides are then weighed according to their % composition accurately in the digital weighing machine and mixed properly.

B) Mixing:

After getting the accurate proper weights of major oxides, they need to be homogeneously mixed. This mixing of major oxides is completed in abrasion testing mixer machine. The fixed 10 gm mixture of weighted percentage composition of all the major oxides (Al_2O_3-$CaCO_3$-SiO_2-MgO) is placed in the three plastic containers. These plastic containers are then put in the 3 rotating chambers of the mixer. It takes around 6-7 hours to complete the one lakh revolutions which are appropriate for proper mixing. Mixing must be homogeneous and perfectly mixed.

C) Pelletization:

Now the spherical shape pellets are made from the total slag sample obtained after mixing oxides sample by the help of distilled water and then kept in the dish plate. Pelletization is needed because the platinum crucible is very small and after pelletization the slag sample is compacted.

D) Drying:

The dish plate carrying the spherical pellets is put in the oven for 3-4 hours for drying up to 120°C. Drying of the pellets will remove the moisture from them. Temperature of the Owen must be maintained around 120°C.

E) Furnace Heating:

The dried spherical pellets are put in the platinum crucible and platinum crucible is placed in the open hearth furnace for heating up to 1600°C which takes around 7 hours for complete unity of slag material due to diffusion. This temperature was taken as at this temperature only blast furnace slag comes out, so firing will be done at this temperature. If the mixing will be done homogenous, then firing will be proper.

F) Quenching:

When the melting of slag is done completely, then slag was quenched in water at normal temperature. After holding platinum crucible for some time in furnace, it was taken out immediately and slag droplets were immersed in water. This will be done when the required temperature is reached slowly but surely.

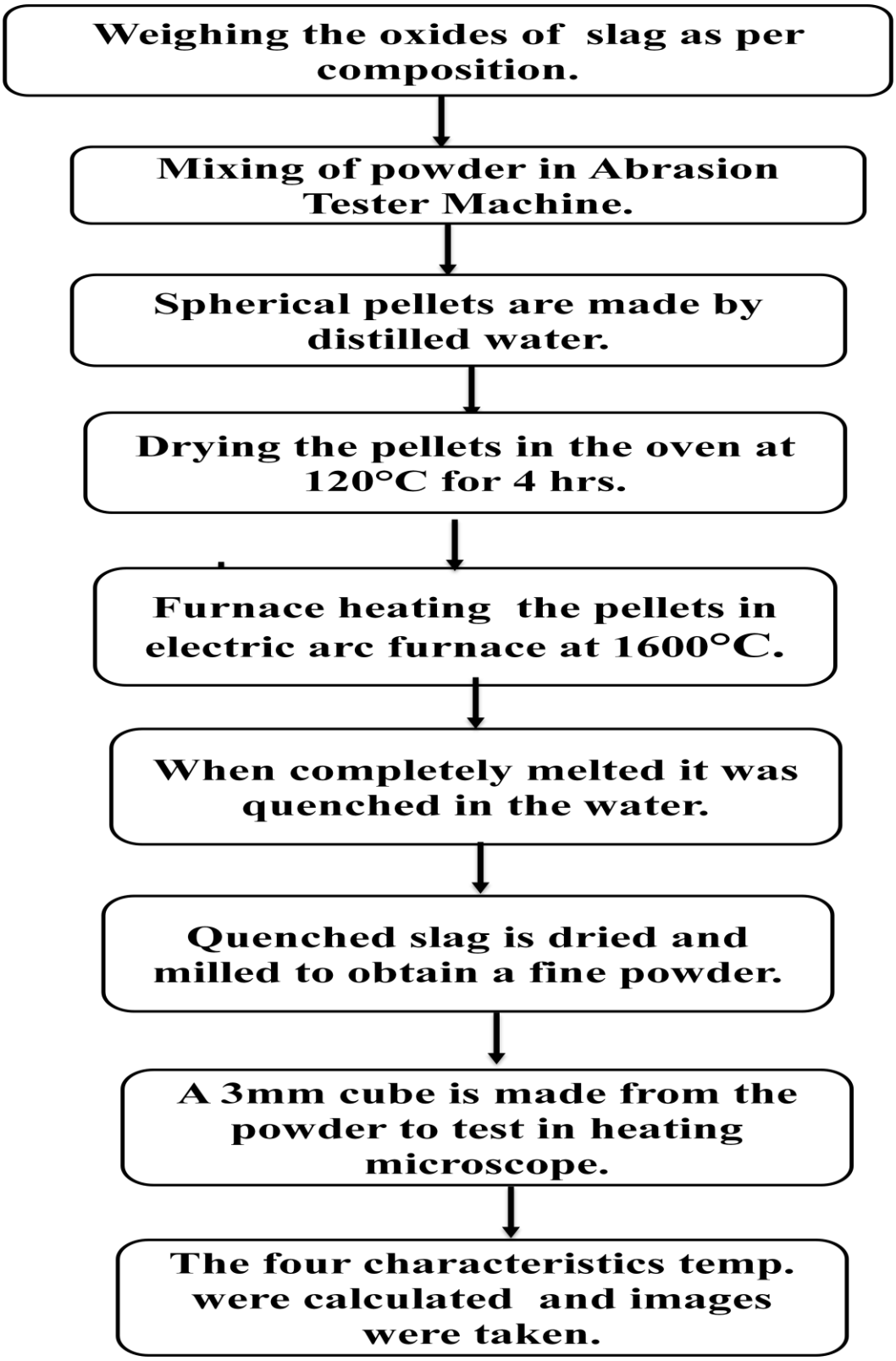
G) Grinding:

After quenching slag appears as a glassy state and was put in oven up to 120°C to take away moisture from slag till 3-4 hours. Then the dried slag was crushed and milled into a very fine powder. We obtain a desired synthetic fine homogeneous powder of slag for experiment.

H) Cleaning:

When the heating and and quenching is completed, the crucible used is cleaned by using diluted HCl (having 50% water + 50% Conc. HCl). The process of cleaning usually takes 2 days and after that the gel formed slag is washed out that was stucked in the crucible.

Experimental details



CHAPTER- 4

RESULT AND DISCUSSION

4.1. Different Combinations of Synthetic Slag

Al_2O_3 (%)	C/S Ratio	MgO Variations (%)
25	0.9	4
25	1.0	6
25	1.1	8
25	1.2	10

Table 1 – Combination of various slag possible by varying basicity

For each value of C/S ratio or MgO with fixed Al_2O_3, there can be 16 different slag combinations which are possible. There can be various combinations of the slag that can be made synthetically.

SI. No.	Al_2O_3	SiO_2	CaO	MgO	CaO/SiO_2 (C/S)
1	25	37.36	33.63	4	0.9
2	25	36.31	45.67	6	0.9
3	25	35.78	46.0	8	0.9
4	25	34.21	43.9	10	0.9
5	25	35.5	50.7	4	1.0
6	25	34.5	49.28	6	1.0
7	25	33.5	33.5	8	1.0
8	25	32.5	32.5	10	1.0
9	25	33.8	37.2	4	1.1
10	25	32.85	36.15	6	1.1
11	25	31.9	35.1	8	1.1
12	25	30.95	34.05	10	1.1
13	25	32.37	38.73	4	1.2
14	25	31.36	37.64	6	1.2
15	25	30.45	36.55	8	1.2
16	25	29.54	35.46	10	1.2

Table 2 – Chemical composition (in wt. % of slag)

4.2. Experimental Results and Discussions

Sl.No.	Analyzed composition			Experimental			Empirical calculation		
	Al_2O_3 (wt. %)	CaO/SiO_2	MgO (wt. %)	ST (^oC)	HT (^oC)	FT (^oC)	ST (^oC)	HT (^oC)	FT (^oC)
1	25	0.9	4	1274	1291	1381	1278	1298.54	1388
2	25	0.9	6	1279	1296	1397	1281	1298.52	1399
3	25	0.9	8	1286	1301	1413	1284	1298.49	1411
4	25	0.9	10	1291	1307	1430	1287	1298.47	1422
5	25	1.0	4	1308	1329	1412	1309	1330.94	1413
6	25	1.0	6	1312	1330	1425	1312	1330.92	1425
7	25	1.0	8	1316	1332	1438	1315	1330.89	1436
8	25	1.0	10	1319	1334	1451	1317	1330.87	1448
9	25	1.1	4	1342	1366	1442	1340	1363.34	1439
10	25	1.1	6	1344	1365	1452	1343	1363.32	1451
11	25	1.1	8	1346	1363	1462	1346	1363.29	1462
12	25	1.1	10	1347	1361	1472	1348	1363.27	1474
13	25	1.2	4	1376	1404	1473	1371	1395.74	1465
14	25	1.2	6	1375	1399	1480	1374	1395.72	1477
15	25	1.2	8	1376	1393	1486	1377	1395.69	1488
16	25	1.2	10	1375	1388	1493	1379	1395.67	1500

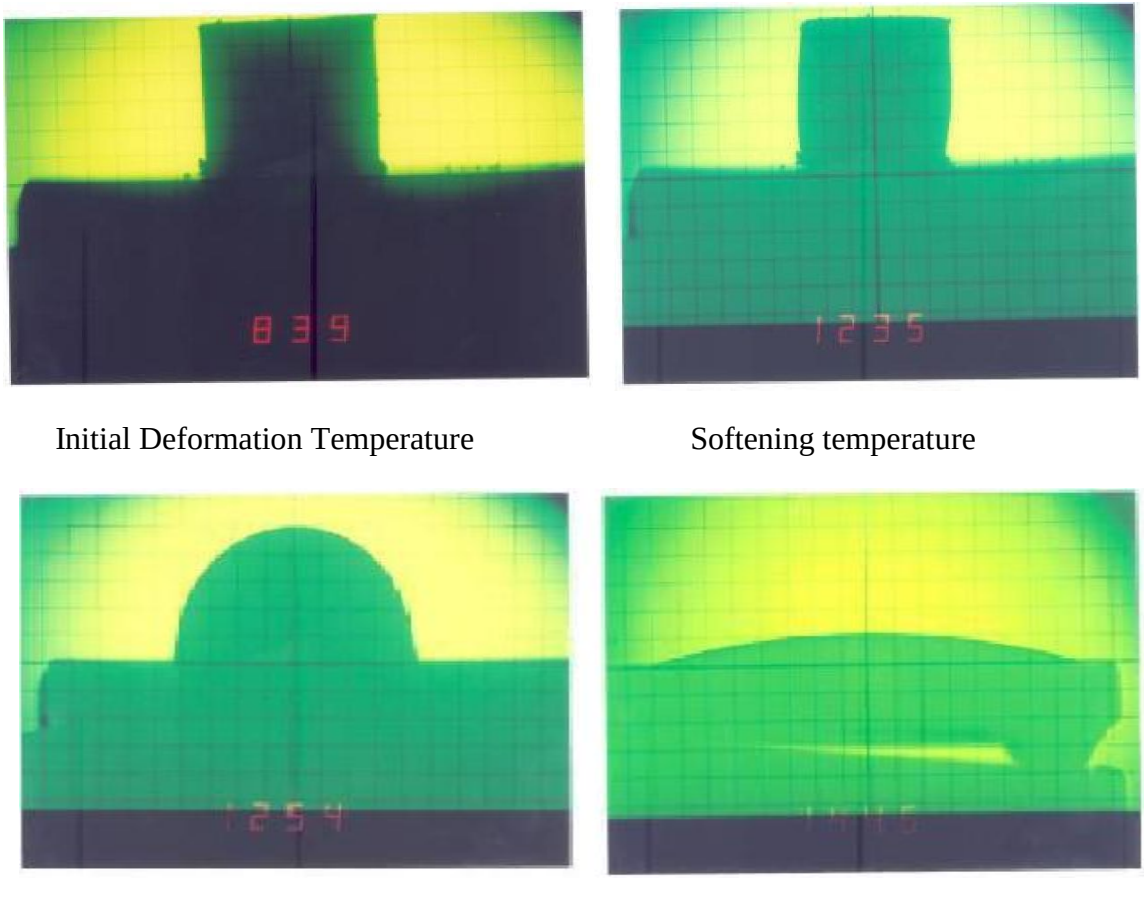
Table- 3 Composition of slags and the present results compared with estimation from empirical equations.

The characteristic temperatures of the selected quaternary ($CaO-MgO-Al_2O_3-SiO_2$) slag system were measured with sixteen different slag compositions based on different levels of CaO/SiO_2 ratio and MgO content at fixed Al_2O_3 value. The Al_2O_3 content was equaled to 25 mass%, the CaO/SiO_2 ratio was varied from 0.9 to 1.2 and MgO from 4 to 10%. The characteristic temperatures of the present investigation and the calculated values are presented in the Table 2. It is obvious that basicity and the MgO content had obvious influence on the characteristic temperatures of the selected slags. Depending on the relative significance of the predictors

(CaO/SiO_2, MgO and Al_2O_3), the individual responses are found out using regression analysis based on the statistical approach are as follows:

$$ST = 994 + 1.37\ M + 310\ R$$
$$HT = 1007 - 0.013\ M + 324\ R$$
$$FT = 1132 + 5.74\ M + 259\ R$$

The experimentally observed and calculated values by statistical model based on empirical of all the three responses for all the sixteen slags are presented in Table 2. It shows that the calculated values of ST differ from the observed values within the range of 4 to -5.Similarly, the difference between the calculated and the observed values of HT falls in the range of -8.53 to 7.67. As FT is concerned the difference between the observed values and the calculated values are in the range of -8 to 7.



Initial Deformation Temperature | Softening temperature

Hemispherical Temperature | Flow Temperature

Fig. 10 – View of flow characteristics of synthetic slag by Leitz High temperature microscope

4.3. Results

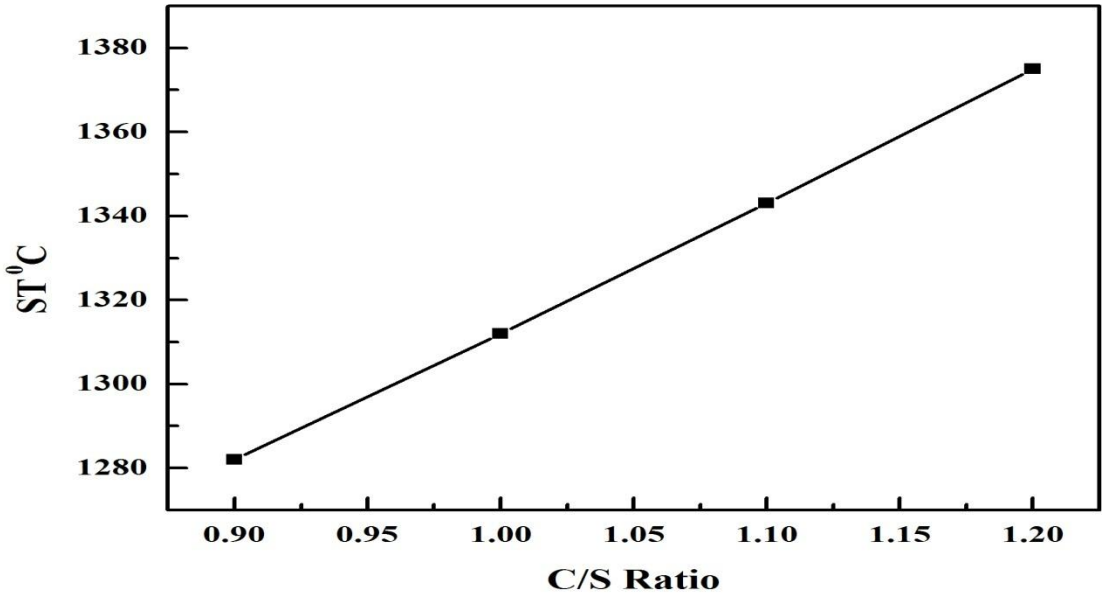


Fig. 11 - Effect of C/S ratio on ST

This graph (fig. 11) shows the relationship between the Softening temperature and C/S ratio. As we can see from the graph, when C/S ratio increases, then the Softening temperature of synthetic slag also increases.

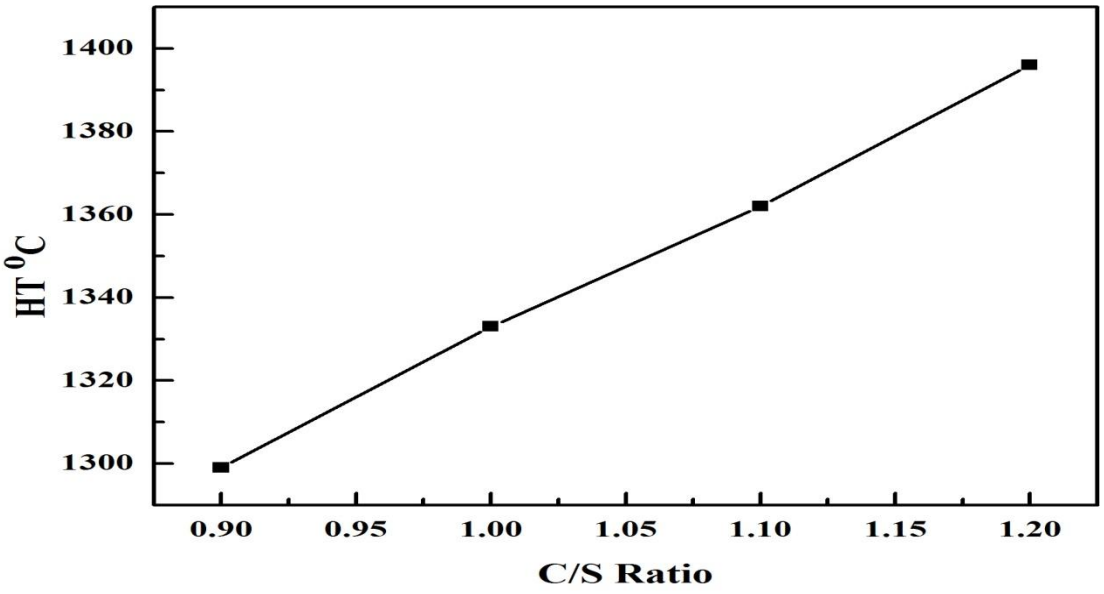


Fig. 12 - Effect of C/S ratio on HT

This graph (fig. 12) shows the relationship between the hemispherical temperature and C/S ratio. As we can see from the graph, when C/S ratio increases, then the hemispherical temperature of synthetic slag also increases.

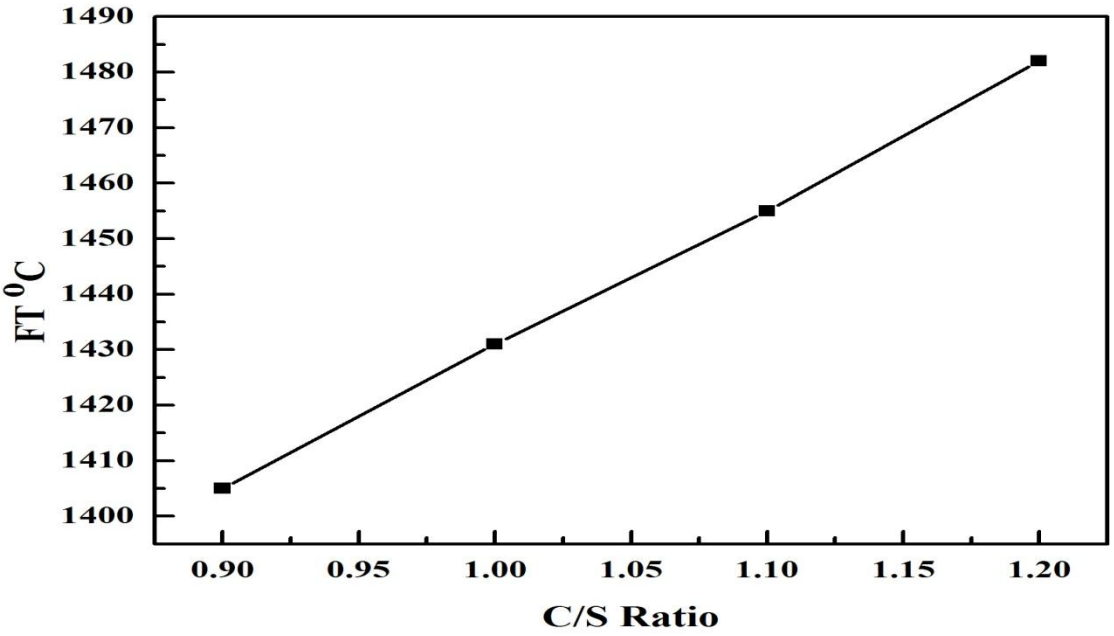


Fig. 13 - Effect of C/S ratio on FT

This graph (fig. 13) shows the relationship between the Flow temperature and C/S ratio. As we can see from the graph, when C/S ratio increases, then the Flow temperature of synthetic slag also increases.

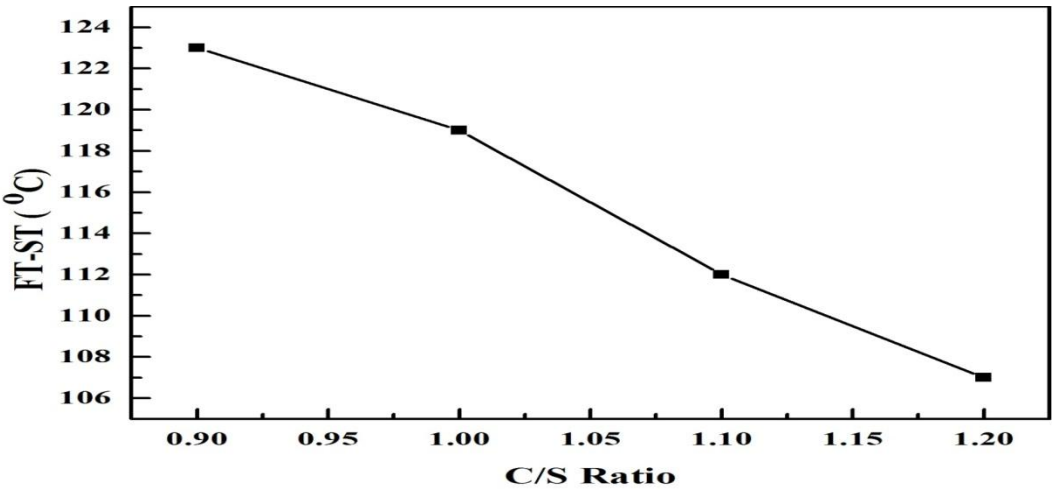


Fig. 14 - Effect of C/S ratio on (FT-ST)

This graph (fig. 14) shows the relationship between the difference of Flow temperature and softening temperature and the C/S ratio. As we can see from the graph, when C/S ratio increases, then the difference between Flow temperature and softening temperature of synthetic slag decreases. Difference between FT and ST depicts width or thickness of cohesive zone. So cohesive zone thickness decreases with increase in C/S ratio having constant Al_2O_3.

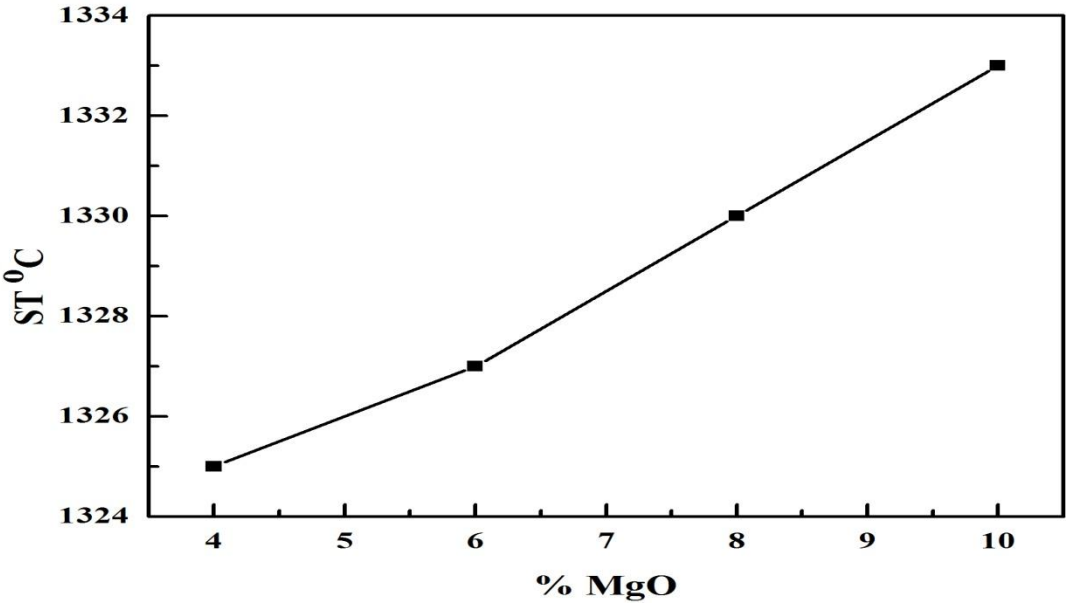


Fig. 15 - Effect of % MgO on ST

This graph (fig. 15) shows the relationship between the Softening temperature and % MgO. As we can see from the graph, when % MgO increases, then the Softening temperature of synthetic slag also increases. This shows that the slag will be softened lower down the furnace and the possibility will be less to interfere with the bed permeability.

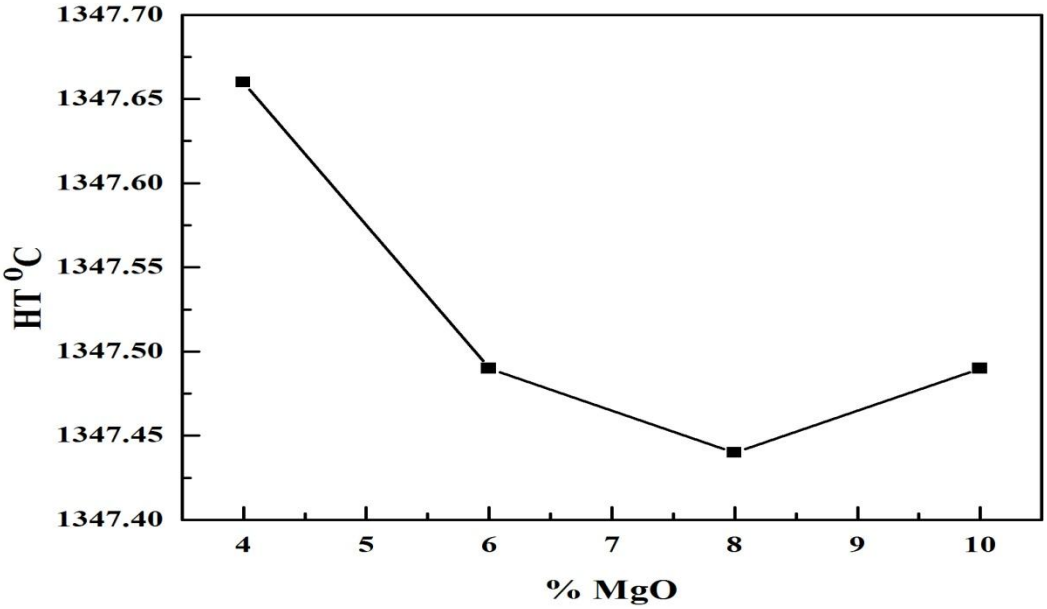


Fig. 16 - Effect of % MgO on HT

This graph (fig. 16) shows the relationship between the Hemispherical temperature and % MgO. The HT is highest when MgO is 4% and decreases with the increase in % MgO till 8%. After that if we increase the % MgO to 10% by keeping Al_2O_3 constant, then HT increases but the increasing slope is less than that of decreasing slope.

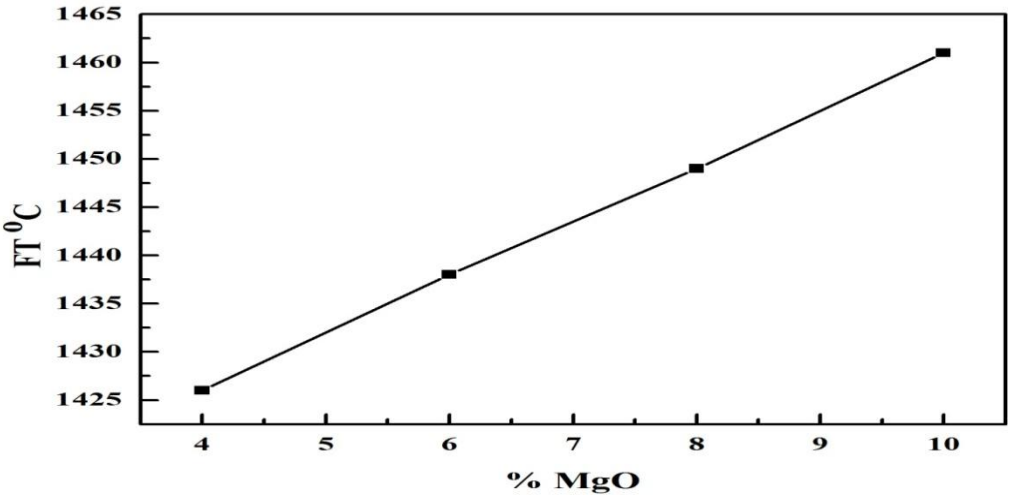


Fig. 17 - Effect of % MgO on FT

This graph (fig. 17) shows the relationship between the Flow temperature and % MgO. As we can see from the graph, when % MgO increases, then the Flow temperature of synthetic slag also increases.

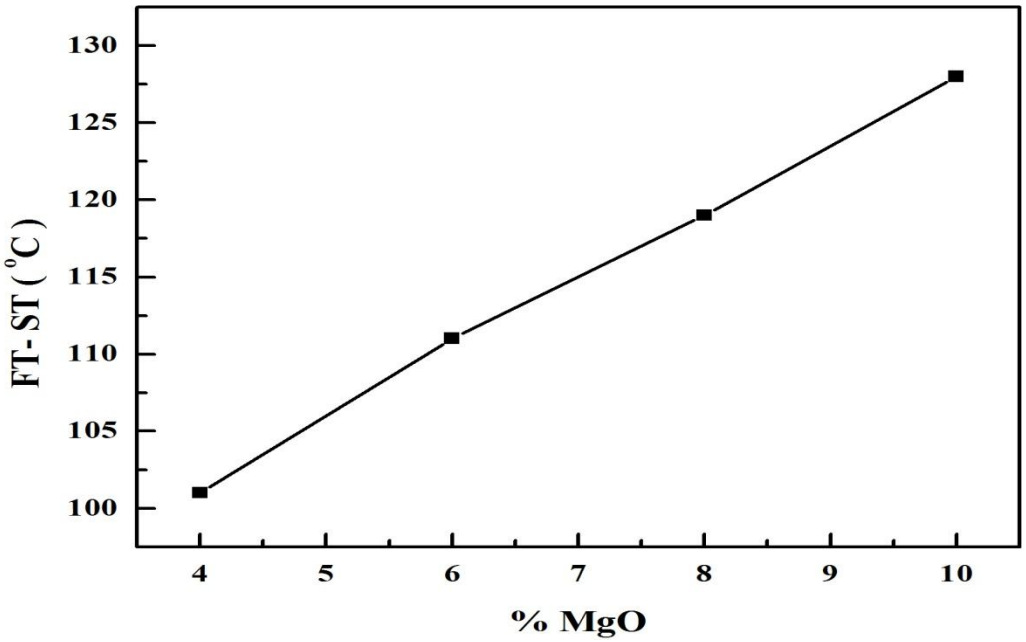


Fig. 18 - Effect of % MgO on (FT-ST)

This graph (fig. 18) shows the relationship between the difference of Flow temperature and Softening temperature and % MgO. As we can see from the graph, when % MgO increases, then difference between FT and ST also increases. This shows that low value of % MgO i.e. 4% is beneficial for obtaining the short slag within the range of compositions.

CHAPTER- 5

CONCLUSIONS

5. Conclusions

1.) It is seen that the characteristic temperatures generally increases with the increase in the C/S ratio of the synthetic slag with fixed high alumina content which is amphoteric in nature.

2.) With the increase in the C/S ratio, the difference between the FT and ST is decreased. So under the composition's ranges that were examined, high C/S ratio is advantageous for the blast furnace operation as it narrows the softening-melting range.

3.) With the increase in % MgO, the ST increases. This shows that the slag will be softened lower down the furnace and the possibility will be less to interfere with the bed permeability.

4.) With the increase in % MgO, difference between FT and ST increases. This shows that low value of % MgO i.e. 4% is beneficial for obtaining the short slag within the range of compositions.

From the obtained result and analysis it was observed that slag with high C/S ratio = 1.2, low % MgO = 4% with a fixed value of 25% Al_2O_3 is best composition obtained. It is beneficial for blast furnace operation and ensures formation of "Short Slag".

Flow characteristic temperatures of the slag had been predicted through empirical equation using regression analysis. It was seen that C/S ratio, Al_2O_3 and MgO are mutually dependent on their effect on flow characteristics. The values that were calculated from the regression analysis were very close to the one calculated experimentally. This validated statistical model get through regression analysis will be helpful in predicting the flow characteristic temperatures of blast furnace slag.

Future Work

The result and data obtained from this experiment can be utilized for getting best slag composition and for smooth running of blast furnace. It can be used to increase its efficiency and productivity. The results can be used for finding out good slag composition to study its effect on iron oxides reduction.

REFERENCES

1.) Nogueira Paulo F. and Fruehan Richard J., Metallurgical and Materials Transactions B, 35 B, 2004, p 829.

2.) Kaushik P. and Fruehan Richard J., Ironmaking & Steelmaking, 33, No. 6, 2006, pp. 507-519.

3.) Clixby G., Softening & Melting of super fluxed sinters and acid pellets, BSC, Ironmaking Session, Tesside Laboratories, International Report,1979.

4.) Potebnyaj et al, Steel USSR 3, 1973.

5.) Biswas A.K., Principles of Blast Furnace Ironmaking, Calcutta: SBA Publications, 1984.

6.) Ghosh Ahindra and Chatterjee Amit, Ironmaking and Steelmaking – Theory and Practice, New Delhi: PHI Learning Private Limited, 2010.

7.) Book: Tupkary R. H., and Tupkary V. R., "An introduction to modern Iron Making", Khanna Publication.

8.) LEE, Y.S., KIM, J.R., YI, S.H. and MIN, D.J; "Viscous behaviour of CaO-SiO2-Al2O3-MgO-FeO slag": *VII International Conference on Molten Slags Fluxes and Salts*, The South African Institute of Mining and Metallurgy, 2004.

9.) U. K. Mohanty: Ph. Dr. Dissertation, R. E. College, Rourkela, (2000).

10.) U.K. Mohanty, R.C. Behera: ISIJ Int., Vol. 43 (2003), No. 12.

11.) BQSF; "Report of the Visit of the Slag Study Group of the Japan Iron and Steel Federation of BQSF", British Quarrying and Slag Federation Limited, June 29, 1978.

12.)Shankar Amitabh, Gornerup Marten, Lahiri A.K, Seetharaman S., Experimental Investigation of the Viscosities in CaO-SiO2-MgO-Al2O3 and CaO-SiO2-MgO-Al2O3- TiO2 Slags, Metallurgical and Materials Transactions B, 38 (6), pp. 911-915.

13.) Osborn E. F. et al.,Process Blast Furnace, Coke Oven and Raw Materials Conference,1953.

14.) Snow R. B., Proc., AIME, 1962.

15.) Ohno A. and Ross H. U., Can. Metall. Q., 2, 1963, p 243.

16.) Kaushik P. and Fruehan R.J, Iron Making and Steel Making, 2004.

17.) Kaushik P. and Fruhen J., Mixed Burden Softening and Melting, Iron Making and Steel Making, Volume 33(Issue 6), 2006, pp. 507-519.

18.) German Industrial Standard 51730.

19.) Y.S.Lee, J.R.Kim, S.H.Yi and D.J.Min; "viscous behavior of CaO-SiO2-Al2O3-MgO-FeO slag". Proceedings of VIII international conference on molten slag, fluxes and salts, The South African Institute of Mining and Metallurgy, 2004, p.225.

20.) Shankar Amitabh, Gornerup Marten, Lahiri A.K, Seetharaman S., Experimental Investigation of the Viscosities in CaO-SiO2-MgO-Al2O3 and CaO-SiO2-MgO-Al2O3-TiO2 Slags, Metallurgical and Materials Transactions B, 38 (6), pp. 911-915.

21.) JIA, J.-Y., BAI, C.-G., QIU, G.-B., CHEN, D.-F., and XU, Y; "Calculation models on the viscosity of Cao-SiO2-TiO2 slag system", VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy, 2004.

22.) Seok Seong-Ho, Jung Sung-Mo, Lee Young-Seok and Min Dong-Joon, ISIJ International, Vol. 47, No. 8, 2007, pp. 1090-1096.

23.) BQSF; "Report of the Visit of the Slag Study Group of the Japan Iron and Steel Federation of BQSF", British Quarrying and Slag Federation Limited, June 29, 1978.

24.) Noritaka Saito, Naoto Hori, Kunihiko Nakashima and Katsumi Mori, Metallurgical and Materials Transactions, Volume 34B, October 2003.

25.) Nakamoto Masashi, Tanaka Toshihiro, Lee Joonho and Usui Tateo, ISIJ International, Vol. 44, No. 12, 2004, pp. 2115-2119.

26.) Verma, R.K.; Ray, H.S; Gosh, A.; Singh, R.N. and Dharnipalan, S.; *Transactions of Indian Institute of Metals, Vol. 32. August 1979.*